STEREO PROCESSING OF MAGELLAN SAR IMAGERY PERFORMED ON A TRANSPUTER ARCHITECTURE[1]

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INTRODUCTION

A stereo processing system has been implemented at the Jet Propulsion Laboratory using a Pacific Parallel Research 16-node transputer architecture. The stereo software involves using an area matching method based on a type of image representation called "Multi-resolution Pyramid" and consists of performing matching of large features first before matching detailed terrain, in a way similar to how human vision works. The result is a high re-solution digital elevation map (DEM) created from a pair of images. All aspects of the stereo processing system utilize parallelism, including image reduction and expansion, band-pass filtering, and correlation. The software is written in C++ with imbedded commands for using the transputer.

The software was originally intended for use with optical images. Recently, radar images appropriate for stereo processing were acquired by the Magellan spacecraft. With few modifications, the software has been successfully run on pairs of standard Magellan mosaic image data records (MIDRs) and has produced DEMs of the surface of Venus with a maximum spatial resolution of 300 meters which is approaching the 75 meter image pixels of the data itself. The details of the algorithm used and its performance are presented. The benefits of using an area matching scheme on radar images are explained.

In order to determine the accuracy of these results for Magellan data, the effects of using mosaicked imagery and of the spacecraft ephemeris were also examined. At the Multi-mission Image Processing Laboratory (MIPL), the MIDRs are built up by mosaicking overlapping orbits of Full-resolution Basic Image Data Records (F-BIDRs). A system was developed for saving from the F-BIDRs the incidence angle profile along the ground track of the orbit and varying the incidence angle across the width of the orbit.

The spacecraft ephemeris was derived from ground-based Doppler tracking with each navigation solution covering a block of 7 or 8 orbits. At the boundaries of the navigation solutions the relative orbit-to-orbit ephemeris errors are large as 700m because the ephemerides are computed from independent numerical integrations and based on different sets of tracking observations. These errors show up in the resultant MIDRs as mis-registrations between adjacent orbits over those boundaries in the along-track and cross-track directions. The cross-track errors create artificial "cliffs" in the digital elevation maps which are based upon the measuring the parallax between pairs of MIDRs. These "cliffs" can be as great as 1000 meters in height.

STEREO PROCESSING ALGORITHMS

Multi-resolution pyramid representation [Reference 1] consists of three operators, Reduce(R), Expand(E), and Laplace(L). The Reduce operator acts as a subsampler as well as a lowpass filter by applying a Gaussian filter on an image while decimating the image. The Expand operator enlarges the reduced image to the original size by reinserting the missing pixels with the lowpass filtered result of the neighboring area. The Laplace operator is a simple subtracter which acts as a highpass filter by subtracting the lowpass filtered image from the original image.

These operators are applied to an image successively to create image representation pyramids. The sequence of reduced images (low pass filtered images) is called Gaussian Pyramid and the sequence of highpass filtered images is called Laplacian Pyramid. The Laplace operator acts as a bandpass filter when it is applied to an already lowpass filtered image (Gaussian pyramid above level O).

A modified version of Gaussian and Laplacian pyramids can be constructed with the FSD (Filter, Subtract, Decimate) method. In the FSD method, the Reduce operator is divided into Filter and Decimate operators. The Laplacian pyramid is created from the difference between the two consecutive Gaussian pyramid levels before Decimate operator is applied. Thus, Expand operation is not required in this method.

The important properties of the multi-resolution pyramid representations above are its scale and translational invariance and its ability to characterize images in statistically independent components. The highest level of pyramids (level n) may be determined by building the pyramids until the correlation of the bandpass filtered images (Laplace pyramid level n) over an entire area is successful or it may be set to a reasonable level prior to the matching process. The Laplacian pyramid is applied for correlation process instead of the Gaussian pyramid for feature extraction and noise removal. For noisy data, the correlation process must be avoided for the Laplacian pyramid level O.

The disparity result of the highest pyramid level (lowest resolution) is then expanded to be applied as a search area prediction for the next pyramid level correlation process (predicted correlation). The process of disparity expansion and predicted correlation is continued until the pyramid level O (highest resolution image pair) is reached. Thus the process completes a loop of building pyramids from high to low resolution and processing them from low to high resolution.

For each resolution level, the template size is kept the same. The same size template in multiple resolution implies multiple size templates in a single resolution. For the areas with no successful match, their predicted disparities are taken as possible disparities. Such substitution can be viewed as employment of the larger template correlation result when the smaller template does not contain enough correlatable features. Thus, the resulting disparities reflect adaptive template size correlation where the template size is determined based on the area correlation result.

The similarity measures employed for image matching process are in general normalized correlation or least squares correlation. The presented technique employs normalized correlation followed by surface fitting (quadratic polynomial fit) to achieve sub-pixel accuracy.

The match process starts at the highest pyramid level employing predicted disparities of (0,0) over the search area bounded by the expected maximum disparity in the sample and line direction defined by the user. For the rest of the pyramid, the correlation search area is limited to template size plus 5 pixels (in both sample and line direction) and the center of the search area is defined to be template center plus the predicted disparity obtained by expanding the disparity of the previous level. The disparity is measured by the displacement in sample and line direction between the location of a template in one image and its corresponding location in the other image where the corresponding location implies the location which produced the highest correlation. After correlation process is completed for each template over the entire search area, the correlation score array is examined for the maximum value. The maximum correlation value is tested against the similarity threshold and the areas whose similarity is less than the threshold are either interpolated using neighboring disparity values (lowest resolution) or substituted with the predicted disparity. The true maximum location and score can be estimated by fitting a quadratic surface function on the correlation score array.

The quality of computed disparity can be quantitatively described per pixel by the corresponding similarity distance and applied resolution level. The resolution level states the final template size employed and the correlation score states the confidence of the match. The disparity measure can be verified by geometrically warping a template image according to the computed disparity and comparing the warped image with the search image. The comparison can be made simply by taking the difference of the two images.

In the case of a digital elevation map generation application, one may apply orthographic projection to the stereo pair and compare the rectified pair. One can also generate a series of rendered scenes using the rectified image and the elevation map for further verification and understanding of the geological structure.

In general, the multi-resolution approach does not require more computation time than single resolution approaches since the search area is much smaller in multi-resolution correlation. Though the image matching process in any resolution scheme is computationally intensive, since the computation is localized, the process can be parallelized easily. The presented technique has been implemented in distributed memory architectures, the MARK IIIfp/JPL-CIT hypercube and the Transputer system by QLS (Quantum Leap System). The implementation decomposes data with overlapping search area between nodes to minimize node-to-node communication, Thus, the execution speed up is linear and implementation to other distributed architectures is simple.

THE MAGELLAN MISSION

From September 1990 until September 1992, the Magellan spacecraft observed the surface of Venus, using Synthetic Aperture Radar (SAR). During that time the spacecraft's ground track swept across Venus three times referred to as mapping "cycles". The SAR was operated differently on each of the three cycles, in order to maximize the science return. The goal of the first cycle was to image as much of the surface as possible using a "left-looking" mode (i.e., the radar was boresighted to the left of the ground track as seen by an observer facing in the direction of the motion). In the third cycle, the radar was again used in a left-looking mode, but at a different off-nadir angle than in cycle 1. Because the incidence angle of the radar at the surface was 10-20 deg different between cycles 1 and 3, overlapping images from the two cycles can be combined to produce stereo images and high-resolution digital elevation maps (DEMs) of the surface.

The processing of the radar echo data into images requires knowledge of the spacecraft's orbit. This orbit knowledge can be obtained to sufficient precision from Earth-based Doppler tracking measurements. However, when radar images from multiple orbits are combined into mosaics necessary for geological mapping, typical relative errors between orbit solutions become evident as discontinuities running through the images. Relative errors in orbit solutions cause even larger artifacts in stereo products because stereo processing is particularly sensitive to ephemeris errors.

BASELINE MAGELLAN ORBIT DETERMINATION

The baseline technique for determining Magellan's orbit uses Earth-based Doppler measurements of the spacecraft velocity acquired during the periods when the spacecraft antenna is pointed at the Earth. The spacecraft position can be determined using these measurements to an absolute accuracy, relative to the center of Venus, of about 10 km, and a relative orbit-to-orbit accuracy of about 1 km. Although this level of accuracy is adequate for processing the radar data, it is not sufficient to eliminate artifacts in image mosaics and stereo products. For example, a 1-km along-track relative error between consecutive orbits causes a noticeable discontinuity in an image mosaic.

Relative orbit-to-orbit ephemeris errors are largest across so-called "navigation boundaries", i.e., the boundaries between the blocks of 7-8 orbits covered by each navigation solution. The spacecraft ephemeris within each block (or "arc") is computed via a single continuous numerical integration of the equations of motion, and is based on a single set of tracking observations. Relative ephemeris errors across navigation boundaries are larger than those within a navigation solution because the ephemerides are computed from different numerical integrations and are based on different sets of tracking observations.

THE MAGELLAN RADAR SYSTEM AND STEREO PROCESSING OF SAR IMAGES

During each mapping pass, the Magellan radar observed a long narrow North-South swath of surface. The basic image is typically about 300 pixels wide by about 200,000 long, where the pixel size is 75m. Series of image swaths were mosaicked together at selected latitudes. These mosaics are 7168 by 8192 pixels in size and subtend an area of surface about 5° on a side. The number of orbits of data used in a mosaic varies from about 30 at the equator to over 160 near the poles. Because they are comprised of so many orbits of data, mosaics contain many navigation boundaries, and therefore many opportunities for relative errors to produce artifacts.

Mosaics from cycles 1 and 3 of the same area of surface are combined using stereo algorithms to obtain high-resolution DEMs. Stereo processing is very sensitive to ephemeris errors: even small errors lead to noticeable artifacts. The figures illustrate this problem. It shows a small region near Maxwell Montes on Venus where stereo processing has been applied using the standard Earth-based ephemeris. The vertical bands measure the along-track shifts required to align sections of the images. For example, the vertical boundary down the center of the image is caused by a relative along-track error of about 700*m between two cycle 1 navigation solutions. Typical relative cross-track errors in the Earth-based ephemeris produce artificial "cliffs" up to a kilometer high running down the lengths of the DEMs. These artifacts cannot simply be removed cosmetically from the stereo products -- improving the accuracy of the spacecraft ephemeris is the best solution to the problem.

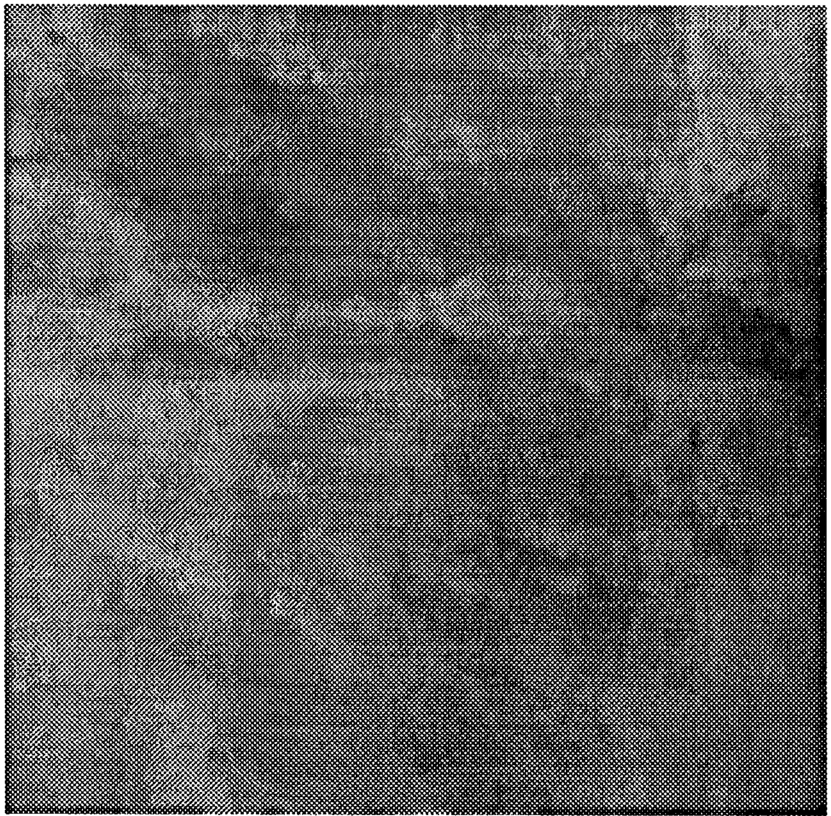

Figure 1: **Relative Cross-Track Pixel Shifts Between Mosaics from Cycle 1 and Cycle 3 Showing Nav. Boundary**

Figure 2: **Relative AlongTrack Pixel Shifts Between Mosaics from Cycle 1 and Cycle 3 Showing Nav.** Boundary

MAGELLAN ORBIT DETERMINATION USING SAR LANDMARK MEASUREMENTS

The fact that ephemeris errors are noticeable in radar mosaics indicates that SAR imagery has high enough resolution to contribute orbit information. Measurements of distinct features ("landmarks") in Magellan radar images provide a means for improving the accuracy of the spacecraft's ephemeris. A method has been developed to combine landmark measurements with the standard data set of ground-based Doppler measurements to compute an improved spacecraft ephemeris [Reference 2]. The technique has been demonstrated to significantly improve the accuracy of the orbit estimate. The landmarks provide Venus-relative information which helps to tie one orbit to the next and reduce relative ephemeris errors.

The method described in the reference applied only to individual orbit-determination arcs. The technique has been extended to multiple arcs, where measurements of landmarks common to multiple arcs are used to tie the arcs together; i.e., the orbit solutions for the arcs are allowed to vary independently, but they are constrained by measurements of common landmarks. Although this method is useful for tying together long series of consecutive arcs, it is especially appropriate for computing ephemerides for stereo processing. In the example to be described in the paper, the technique was applied to 7 arcs, 3 from cycle 1 and 4 from cycle 3 that covered much of the same terrain. Landmarks measured on two or more arcs served to reduce the relative errors not only between arcs on the same cycle, but also between cycle 1 arcs and cycle 3 arcs. The high precision of the resulting ephemeris led to a more accurate and artifact-free DEM.

Reference:
[1] Burt, P.J., Fast Filter Transforms for Image Processing, Computer Graphics and Image Processing, pp. 20-51, 1981.

[2] Chodas, P.W., T-C. Wang, W.L. Sjogren, and J.E. Ekelund, "Magellan Ephemeris Improvement Using Synthetic Aperture Radar Landmark Measurements", Paper AAS 91-391, AAS/AIAA Astrodynamics Conference, Durango, Colorado, August 19-22, 1991.